Methane Production from a Pilot-Scale Fixed-Film Anaerobic Digester and Plug-Flow Digester Loaded with High-Solids Dairy Manure

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Stephen Hoyt, Project Engineer
The DUBARA COMPANY
Castleton, New York 12033

Abstract

Three pilot-scale anaerobic digesters (two of a unique fixed-film design, of which one was fed micronutrients, one not, and an identically sized plug-flow digester, which served as the control) were monitored for methane production as a comparative indication of performance. All of these pilot-scale digesters were loaded daily with high-solids dairy manure, passed through a 1.5" x 3" mesh screen, directly from The Spring Valley Dairy (which uses sand bedding). Testing took place over a two and half month period first at 13 day and then 5 day Hydraulic Retention Time (HRT) loading rates. Neither fixed-film digester experienced any plugging difficulties. Average methane production at 5 day HRT of the fixed-film digester fed micronutrients was greater than the control by 17.65%; and the fixed-film digester not fed micronutrients averaged 14.37% more methane than the control. Average production of methane per volume of digester per day increased from .51 volumes of methane per volume of manure at 13 day HRT to .95 at 5 day HRT, for fixed-film with micronutrients and .46 at 13 day HRT to .91 at 5 day HRT, for the fixed-film without micronutrients. Informal observation by five individuals confirmed a large decrease in offense odors from effluent at 5 day HRT and 13 day HRT, for all digesters, as compared to five days old untreated manure.

Equivalent methane production/vol. manure/day at 5 day HRT was approximately two-thirds of the production at 13 day HRT for the fixed-film digesters, which could be sufficient to meet gas needed for electrical production on many farms, since many farm digesters produce an excess of gas. In addition, it was observed that effluent from the digesters (treating less than 1% of the total waste stream) which were emptied into the manure storage pit for the farm, actually activated the pit to produce large amounts of biogas, reduce crusting, solids and for the first time, also largely reduced the odors from the pit stored manure when spread.

The fixed-film digester without micronutrients was later drained at the end of the testing period and reloaded to test the recovery time of the fixed-film digester. Restart to previous production levels was accomplished within two days.

Introduction

The advantages of anaerobic digestion of dairy manure are outlined in the *Project Proposal for the Testing of Whole Dairy Manure Using a Unique Fixed-Film Anaerobic Digester* by Stephen Hoyt. In particular, main advantage of short HRT rates is lower capital costs of a large-scale system due to the reduced digester reactor size. The objective of this project was to study the performance of a unique design of attached growth or fixed-film anaerobic digester to determine it's ability to process whole dairy manure at low HRT. In addition, the effect of added micronutrients was tested with the fixed-film design.

Goals of the pilot project, as stated in the project proposal, were to examine the following possible design innovations on a small scale for later application to a full-scale system:

1) performance testing of a fixed-film anaerobic digester with whole dairy manure;

2) analysis of heavy sediment settling rates;

3) testing of sediment removal system;

4) use of micronutrient addition to enhance the digestion process;

5)comparison of process rates when operating under mesophilic and thermophilic conditions.

Testing of this fixed-film design operating in the thermophilic range, was not accomplished due to time constraints.

Materials and Methods

Each of the digester's reactors was constructed of a 55-gallon plastic drum laid horizontally at 15º, plumbed with an inlet, and two outlets for wasting out light and heavy solids. The digesters were all insulated and temperatures were maintained at approximately 100º F. Surface to volume ratio for both of the fixed-film digesters was approximately 45 m^2/m^3 whereas the same ratio for the control was approximately 9 m^2/m^3. Fresh manure from the Spring Valley Dairy was loaded daily directly from the trench exiting the barn. Feed material from the barn contained a significant amount of sand from sand bedding and was often diluted from milking parlor wash water or rain water. Consequently, total solids and waste strength varied considerably from an estimated 2% to 10% total solids. Fed material was agitated and screened through a 1.5" x 2.5" mesh to remove large solid particles over 1.5" and straw, which accounted for a very small portion of the total manure sample. The loading rate was determined by measuring a set quantity of fresh manure loaded daily into individual feed tanks, indicated by graduated floating depth indicators.

Biogas production, using a water displacement device designed by Mr. Hoyt, and carbon dioxide content, using a Fyrite Gas Analyzer, were recorded daily. After an initial start-up period in which each digester was half loaded with seed material from the manure pit and half fresh manure and otherwise unloaded for approximately three weeks. After the digesters were all producing about 40% CO2, the digesters were then loaded at an approximate 13 days HRT rate for 1.5 weeks. After a brief three day period at 11.2 HRT the loading rate was than moved directly up to 5 day HRT and maintained at that rate for more than one month.

Particular challenges of the design which were overcome included development and testing of the gas measuring devices capable of measuring volumetric rates ranging from less than 10 gallons per day to several hundred gallons per day and construction of a lifting device for taking large manure samples, after frequent failure of the loading pump due to small stone particles. These unforeseen difficulties, a very limited budget and funding delays resulted in some schedule shifts and an inability to due any testing under thermophilic conditions.

Micronutrient feed consisted of iron, nickel, and cobalt in the form of iron sulfide, nickel chloride, and cobalt chloride at a rate of 10 mg/L (of digester volume) .07 mg/L and .07 mg/L respectively. However, iron sulfate was substituted by iron filings (well in excess of 10 mg/L) at approximately two weeks before ending regular daily loading.

The lower exit of each digester consisted of a pipe flange, attached to a rubber 'T' pipe section of which one leg extended up to the liquid level of the digester as a vent, and the other leg was attached to a removable capped section of pipe. Sediment was scraped into this capped section of pipe by a long rod with a paddle on the end which extended out through a long hose above the liquid level so that the rod could be handled without any gas escaping from the digester. The rubber 'T' pipe was then clamped shut so that the capped pipe section could be removed and emptied of sediment.

Results and Discussion

Average carbon dioxide production was 45.34% for Digester 3, 43.22% for Digester 2 and 49.81% for Digester 1. The remaining volume for all was assumed to be mostly methane. Average methane production is shown in Table 1, for the 13 day HRT, and Table 2 and the graph "Methane Production 5 day HRT", for 5 day HRT. Digester 3 represents the fixed-film design which was fed micronutrients, Digester 2 was also fixed-film but not fed micronutrients and Digester 1 represented the control with no fixed-film media nor fed any micronutrients. At 5 day HRT Digester 3 produced 29.01% more methane than the control and digester 2 produced 20.28% more methane than the control. However, it was discovered at the end of the experiment that sediment accumulations in the feed tanks had influenced the position of the graduated floating depth indicators. Actual volumes of manure loaded to Digester 3 were found to be 16% above the control and Digester 2 was found to have 8% more volume loaded than the control. These differences could have had a corresponding impact on total biogas production. Therefore, by increasing Digester 2 by 8% and Digester 1 (the control) by 16% we see a narrower difference in average methane production rates. However, despite these changes, Digester 3 still produced 17.65% over the control and Digester 2 produced 14.37% more methane than the control.

Table 1
Average Methane Production (in gallons) at 13 day HRT

Digester 3	Digester 2	Digester 1
26.32	24.05	No data

Methane production at 13 day HRT for the control is unavailable due to a temporary failure of the gas measuring device for the control during this period.

Table 2
Average Methane Production at 5 day HRT

	Digester 3	Digester 2	Digester 1
Actual (gal.)	49.43	44.02	35.09
% Above Control	29.01	20.28	-
Corrected (gal.)	49.43	47.54	40.71
% Above Control	17.65	14.37	-

Likewise, methane production per volume of manure (Table 3, 4) at 5 day HRT (based on the corrected manure volumes loaded for each) was greatest for Digester 3 at 3.95 volumes of methane per volume of manure (15.48% more than the control). Production per volume of manure was 3.83 volumes of methane per volume of manure (12.69% more than the control) for Digester 2. At 13 day HRT gas productions for Digesters 3 and 2 were 6.09 and 5.56 volumes of methane per volume of manure. Therefore, average methane production per volume of manure was approximately 65% and 69% at 5 day HRT of that produced at 13 day HRT for Digesters 3 and 2 respectively. This could be a sufficient rate of production for many farms to supply most of the electrical needs from cogeneration of biogas. However, methane production could be stronger for a longer testing period since there was only a limited time for a biofilm to develop which can require as much as a six-month period for many industrial low-solids fixed-film designs. Also due to the cylindrical design of the digester it is likely that portions of the surface area of the media were not in efficient contact with the flow manure, an important factor in fixed-film performance. On a large scale, with proper manifolding through a rectangular digester, more efficient contact with media would be possible.

Table 3
Average Methane Production/Volume of Manure at 13 day HRT

Digester 3	Digester 2	Digester 1
6.09	5.56	no data

Table 4
Average Methane Production/Volume of Manure at 5 day HRT

	Digester 3	Digester 2	Digester 1
	3.95	3.83	3.34
% Above Control	15.48	12.69	0.00

Another indicator of performance, average methane production per volume of digester, is shown in tables 5 and 6. The highest production per volume of digester was achieved by Digester 3 at 5 day HRT .95 volumes/vol. (of digester) /day. The results for Digester 3 fall in the same range as those found by Lo et al[1] for a fixed-film reactor loaded with filtrate dairy manure at 6 day HRT of .89 L/L-day and at 4 day HRT 1.42 L/L-day. However, the plug-flow control performed better at .78 vol/vol-day than Lo et al. at .53 L/L-day for 5 day HRT.

Table 5
Average Methane Production per Volume of Digester at 13 day HRT

Digester 3	Digester 2	Digester 1
.51	.46	no data

Table 6
Average Methane Production per Volume of Digester at 5 day HRT

Digester 3	Digester 2	Digester 1
.95	.91	.78

One unexpected result of the project was the impact of the pilot reactors effluent on the biological activity in the 60 day manure storage pit for Spring Valley Dairy. Prior to operation of the pilot, the stored manure typically had a thick crust of solids and produced very strong odors when spread. After more than a month of operation there was a noticable change in the consistency of the stored manure to a black very liquidy substance (there was no significant rain during this drought period) and a black bubbly foam formed on the surface as large amounts of gas bubbled off continuously. In addition, it was observed that, when spread, there were not the usual strongly offensive odors. Instead a rich, ammonia-like smell was reported which dissipated quickly during spreading. Since the pilot project has ended, the stored manure in this pit has returned to it’s previous characteristics as evidenced by the thick crust and strong odors.

At the end of the testing period the fixed-film digesters were inspected for plugging or clogging of the media due to heavy solids content of the manure. Although there was an accumulation of heavy solids including sand at the bottom of the digester, the media remained clear and there were no apparent restrictions on the flow of the manure in and out of the digester.

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[1] Lo, K. V., P. H. Liao, N. R. Bulley and S. T. Chieng, ”A Comparison of Biogas Production from Dairy Manure Filtrate Using Conventional and Fixed-Film Reactors,” *Canadian Agricultural Engineering*, 26, p. 73-8, 1984.

Observations on sediment settling were made after agitation in the lift system load bucket, in the inlet plumbing, and in the digesters themselves. Although some settling did occur in the load bucket after agitation, and in the inlet plumbing and preheat tanks, most settling occurred in the digesters themselves. Sand accumulations at the end of the experiment occupied an estimated 6% of the total volume. However, the sediment removal system was able to be used to extract perhaps an additional 2%. This scraper sediment removal system did function well as a method of removing heavy solids, but was difficult to use manually and eventually one of the rods (of weak construction) failed.

At the end of the testing period loading was discontinued for Digester 3 while gas production continued to be monitored (as shown in “Methane Production - Discontinued Loading). Also, Digester 2 was drained and then reloaded completely with raw manure the following day to observe the restart time required of the fixed-film. Within two days (as shown in “Biogas Production, Fixed-Film Digester”) the digester was producing approximately the same amount of biogas at 34% carbon dioxide.

Conclusions

The design of this unique fixed-film anaerobic digester allowed for continuous loading of high-solids manure with sand from sand bedding without plugging of the media as typically reported for fixed-film digesters loaded with high-solids manure. Heavy sediment accumulations in the digester indicate that large-scale design must allow for an effective means of removing the sediment in the digester when filled with sand laden manure. A type of automatic sediment removal system, based on the mechanical scaping method appears to be an effective means of getting out the heavy solids. In addition, a chopper agitator or chopper pump could break up solids and straw. The manure characteristics of the Spring Valley Dairy laden with high solids and sand from sand bedding are typical to many farms in Vermont and across the nation.

Results of gas production for this pilot indicate that a fixed-film reactor of similar design on a large-scale could be an effective system for reducing odors and producing sufficient amounts of methane to power a dual-fueled, diesel-biogas cogeneration unit to supply most electrical needs of many larger farms. These farms could then operate off-grid, with proper back up, and benefit from further reduced capital cost associated with generating on the grid. In addition, observations on the biological activity of the storage pit when seeded from the pilot reactors offer a different strategy for power generation on smaller farms in Vermont. Since Vermont law enables farms generating electrical power under 100kW to maintain net metering on the grid, these farms could use a smaller digester (of perhaps 2 day HRT) in conjunction with a covered storage pit for maximum gas recovery from long HRT’s in the pit. Using a more efficient power generation system such as a microturbine generator or fuel cell with such a set up would thereby maximize energy payback.

Micronutrient addition appears have some impact on production based on the consistantly stronger production from the fixed-film reactor fed micronutrients over the fixed-film reactor not fed micronutrients.

The ability of the fixed-film digester to restart in only two days also demonstrates the stability of the biofilm fixed to the media. This presents the additional possibility that thermophilic anaerobic digestion (with double the activity rates but an inherently less stable process) could be combined with this fixed-film design to maintain stability of the thermophilic operation and further improve process rate.